NASA CR-66372

MOMENTUM TRANSFER TO SOLID SURFACES BY N_2 MOLECULES AT SATELLITE VELOCITIES

Technical Report
Contract NAS1 - 2538

Submitted to:

Space Environment Branch
Langley Research Center
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Submitted by:
John W. Boring

Research Laboratories for the Engineering Sciences

University of Virginia

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Report No. EP-4018-139-67U
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ABSTRACT

Measurements have been made of the momentum transfer to solid surfaces by N_2 molecules in the energy range 10-200 eV, the low end of this range corresponding to satellite velocities. The results were obtained by forming a neutral N_2 beam of the appropriate energy, and then measuring the force produced by the beam on a test surface. The dependence of the results on the gross character of the surface and the angle of incidence were studied, with the measurements indicating that the interaction under the conditions of this investigation (surface state not rigidly controlled) was dominated by the gas molecules adsorbed on the surface. An investigation of the dependence of the results on angle of incidence indicates that for rough surfaces the average momentum of the reflected molecules is normal to the surface.

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SECTION I
INTRODUCTION

In considering the motion of a space vehicle through a rarefied atmosphere, it frequently becomes necessary to have knowledge concerning the interaction of the molecules of the atmosphere with the surface of the vehicle. An example of this need is the study of the density of the earth's upper atmosphere using low-density satellites. By observing the decay of the orbit of one of these satellites, it is possible to infer the drag force on the satellite, but in order to use the knowledge of this force to calculate atmospheric density, it is necessary to know how the molecules of the atmosphere exchange momentum with the surface of the satellite.

In April 1963 the Research Laboratories for the Engineering Sciences (RLES) of the University of Virginia began a research program sponsored by NASA under Contract NAS1-2538 to investigate experimentally the interaction with solid surfaces of N_2 molecules moving with satellite velocities. This program has been under the cognizance of the Space Vehicle Branch (Space Environment Branch) of the Langley Research Center, and has as its initial objective the acquisition of information about surface interactions applicable to atmospheric density studies using low-density earth satellites. A report describing the fast molecular beam system developed for making these studies was submitted in November 1965[1]. The present report presents the results of the momentum transfer measurements for various N_2 molecule energies, test surfaces, and angles of incidence.

The following two sections describe the experimental procedure and the results. The final section gives a discussion of the results.

SECTION II
EXPERIMENTAL PROCEDURE

Since the results of this investigation are to be used to relate the drag force on a satellite to atmospheric density, we will discuss here the general problem of atmospheric drag on a satellite and establish the type of laboratory measurements that are required.

Consider the motion of a satellite through the earth's upper atmosphere (which is taken to be stationary). If one ignores for the moment the thermal motion of the molecules of the atmosphere, then it is possible to investigate the drag force on the satellite by considering the satellite to be stationary and having the atmospheric molecules strike the surface of the satellite with a speed equal to the orbital speed of the satellite. This is shown schematically in Figure 1a where molecules moving with velocity v_0 strike a spherical satellite. The molecules moving along one line are shown striking a small area da of the surface of the satellite at an angle of incidence θ and being reflected in various directions. The drag force dF due to the molecules striking da will then be the average change of momentum of the molecules along the direction of v_0, times the rate at which molecules strike da. We then have

$$dF = N(p_0 + p_m) \cos\theta \, da \quad ,$$

where N is the number of molecules per unit area per unit time approaching the satellite, $p_0 = M v_0$ is the momentum of the incident molecules, p_m is the average component of the momentum of the reflected molecules along the direction of v_0 (p_m is taken positive in the direction opposite to p_0). dF can be expressed in terms of the number density of molecules in the atmosphere by using:

$$N = n v_0$$

$$v_0 = \frac{p_0}{M}$$

$$\rho = Mn$$

$$N = n \frac{p_0}{M} \quad ,$$

where n is the number density, M is the molecular mass, and ρ is the

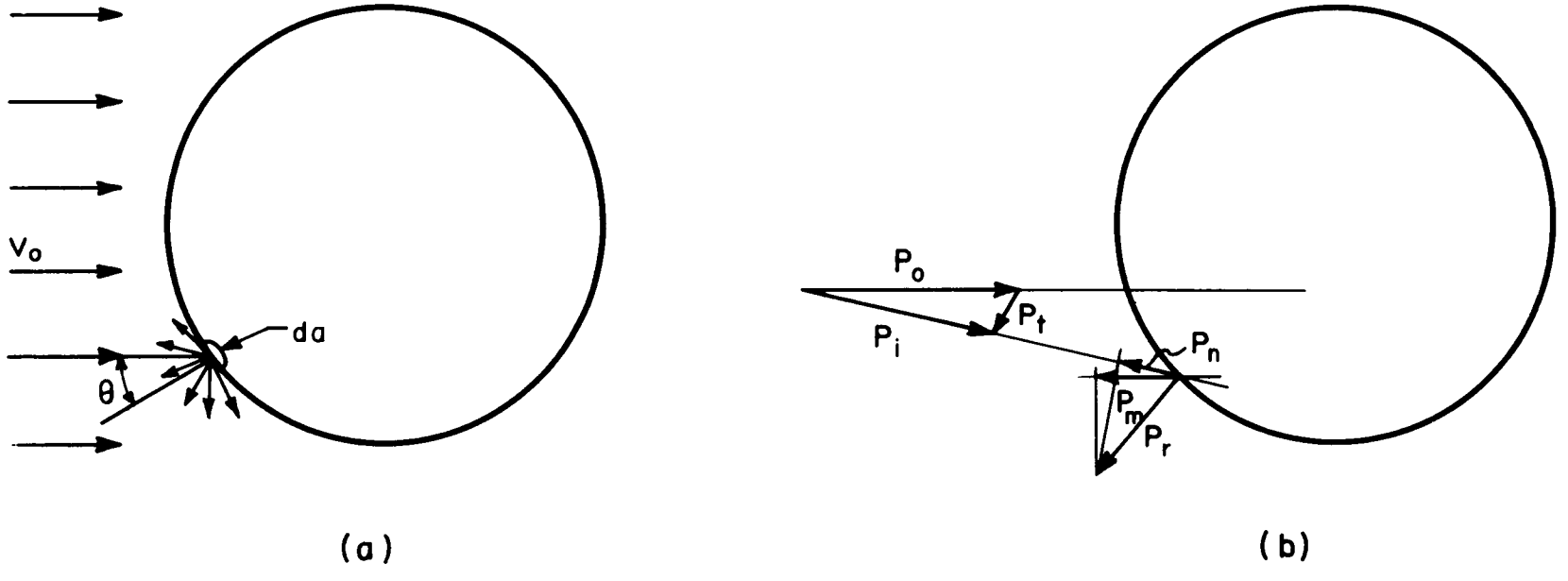

FIGURE 1

atmospheric density (mass/volume). This gives

$$dF = n \frac{p_0}{M} (p_0 + p_m) \cos\theta \, da \quad .$$

The total drag force on the satellite is obtained by integrating dF over the surface of the satellite exposed to the molecules, giving

$$F = \frac{n}{M} p_0^2 \int_s \cos\theta \, da + \frac{n}{M} p_0 \int_s p_m \cos\theta \, da \quad .$$

If A is the projected area of the satellite perpendicular to the direction of motion, then we calculate the drag coefficient C_D from

$$C_D = \frac{F}{1/2 \, A\rho v_0^2} = \frac{2}{A} \left[\int_s \cos\theta \, da + \int_s \frac{p_m}{p_0} \cos\theta \, da \right] \quad ,$$

where the first term in the square bracket gives the contribution to the drag coefficient due to the incident molecules and the second term gives the contribution due to the reflected molecules. Thus it is possible to calculate the drag coefficient for a satellite of any convex shape (so that double reflections are not possible) moving under free-molecule conditions if one knows the ratio $\frac{p_m}{p_0}$ as a function of θ for a given v_0. To take a simple example, if one considers a flat plate moving so that its surface is perpendicular to the direction of motion, then $\theta = 0$ for the entire surface and we get

$$C_D = 2 \left(1 + \frac{p_m}{p_0}\right) \qquad \text{(Flat plate)} \quad .$$

If the temperature of the surface of the satellite corresponds to molecular energies that are small compared to the kinetic energy with which the molecules strike the surface, then it is possible that the molecules remain on the surface for a relatively long time and come off with a momentum p_m which is small compared to p_0. In this case C_D for the flat plate is around 2. If all the molecules were reflected back along the direction of v_0 (specularly) with a speed equal to v_0 then $p_m = p_0$ and $C_D = 4$. The drag coefficient for shapes other than the flat plate can only be calculated by knowing $\frac{p_m}{p_0}$ as a function of θ and then performing the integration over the surface, but the range of C_D will be between 2 and 4 (values larger than 4 can only be obtained if the reflected particles have a velocity larger than the incident velocity). In order to be able to calculate a drag force, then, one must have a knowledge of the ratio $\frac{p_m}{p_0}$ for the molecules and surfaces of interest. Since it is possible to determine the

drag force on a satellite from the decay of its orbit, then if one knows the drag coefficient (as determined from $\frac{p_m}{p_0}$) for all molecular species present it is possible to calculate the number density of the upper atmosphere for various altitudes if the proportion of each of the species is known.

If we consider now the thermal motion of the atmospheric molecules, the molecules approaching the satellite will not all have the same velocity. Both the magnitude and direction of the molecular velocities will be affected, and we must consider what effect this has on the previous discussion. The orbital velocity of earth satellites is in the range 7-11 km/sec. The mean speed of atmospheric molecules at altitudes 200-700 km is in the range[2] 1.0 to 1.4 km/sec, so that one must consider this contribution to the velocity with which the molecules strike the satellite's surface. The relationship among the momentum vectors used in this discussion is shown in Figure 1b. The momentum of the molecules due to the orbital motion of the satellite is p_0 and corresponds to the velocity v_0 in Figure 1a. A momentum due to the thermal motion of the molecules p_t is added to p_0 to yield the momentum p_i with which the molecules strike the surface of the satellite. The average momentum vector of the molecules reflected from the surface is p_r, which has a component p_m along the direction of motion and a component p_n along the line determined by the direction of p_i.

One is concerned here with the effect on the momentum change of the molecules striking the surface of adding to the orbital momentum vector a thermal momentum vector of random direction and of magnitude roughly 1/10 of that of the orbital momentum, thereby changing both the magnitude and direction of the incident momentum. Even though consideration of thermal motion means that the incident momentum at a point on the satellite's surface is not along the satellite's direction of motion, one still need consider only components along this direction since components perpendicular to the direction of motion will be balanced out by corresponding components on the opposite side of the satellite (assuming symmetry of the satellite about its direction of motion). The effect of the thermal motion can be divided into two parts: (1) The component of incident momentum along the direction of motion is either increased or decreased. (2) The average component of re-

flected molecules p_m is altered because the incident momentum vector is changed. The calculation of the effect on the incident momentum is straightforward. One need only consider the distribution in thermal velocities and add their components along the direction of motion to the orbital velocity to get the resultant velocity or momentum that contributes to the drag. The effect on p_m is more complex since the magnitude of p_m will in general depend on both the magnitude and direction of the momentum incident molecules and not on just the resultant component of momentum along the direction of motion. If, however, one can determine the magnitude and direction of the average reflected momentum, p_r (whose component along the direction of motion is p_m) as a function of incident molecule velocity and angle of incidence then p_m can be calculated for any desired case. Determination of p_r involves, in general, a measurement of the angular and velocity distribution of all particles leaving the surface. Such a measurement is experimentally very difficult, especially for the fast, low intensity molecular beams used in the present experiment. One might consider, then, the possibility of using less complete information than the intensity and velocity of all reflected molecules for the calculation of drag coefficients.

It has been shown that if one ignores the thermal motion of the molecules, then a knowledge of the ratio $\frac{p_m}{p_0}$ as a function of angle of incidence is adequate to determine the drag coefficients, and $p_m = p_n$, where p_m is the average component of reflected momentum along the direction of motion and p_n is the average component of reflected momentum along the path of the incident molecules (which is the same as the direction of motion if thermal motion is ignored). Since the thermal velocities are roughly 1/10 of the orbital velocity then it might be expected that a knowledge of $\frac{p_n}{p_i}$ (which in the case of a beam experiment in which the directions of the incident molecules are all the same is equivalent to knowing $\frac{p_m}{p_0}$) would premit one to calculate the principal contribution of the reflected molecules to the drag coefficient. In addition, a knowledge of $\frac{p_n}{p_i}$ as a function of the angle of incidence would allow one to determine how close the direction of p_r is to conceivable limiting directions, such as normal to the surface or in the specular direction. It appears, then,

that a measurement of $\frac{p_n}{p_i}$ for several angles of incidence and for incident molecule velocities in the satellite range is sufficient to establish rather accurately the appropriate drag coefficient for satellites moving under free-molecule flow conditions. The remainder of this section provides a description of the experimental method employed in the present work to measure $\frac{p_n}{p_i}$.

The general procedure in measuring $\frac{p_n}{p_i}$ is to produce a beam of molecules having a known energy corresponding to satellite velocities (the energy in the case of N_2 molecules is 8-18 eV), allow the molecules to strike a test surface at a chosen angle of incidence, and measure the component of force on the test surface along the beam direction. If the rate at which the molecules strike the surface (mol/sec) is determined, then the force divided by the rate gives $(p_i + p_n)$ and since p_i is already known from a knowledge of the energy and mass of the beam molecules then one has sufficient information to determine $\frac{p_n}{p_i}$.

The system for producing a suitable beam of N_2 molecules is described in a previous report[1] in which a typical beam flux of 4×10^{10} mol/sec is obtained, corresponding to a force on a test surface of around 1.5×10^{-6} dyne. Although this is a rather small force, it can be satisfactorily measured with a sensitive torsion balance.[3] One must now consider a method for measuring the rate at which beam molecules strike the test surface (the beam flux). Several methods have been considered, such as allowing the beam to enter an ionization gauge detector in which the pressure rise produced by the beam is measured, but a particularly attractive method of measuring the beam flux is the use of the torsion balance itself, since this would not involve any additional equipment and would obviate the necessity of providing an absolute calibration of the balance for the force measurements. In this method the torsion balance is constructed so that in addition to the test surface the vane of the balance also has a momentum absorber (or momentum trap) attached to it. A momentum absorber is a box constructed so that the beam molecules enter the box, collide a number of times with the inner walls, and then leave through the entrance hole with a velocity distribution which is characteristic of the temperature of the walls. A photograph of the torsion balance used in

the present experiment is shown in Figure 2, where the test surface ($\theta = 0^{o}$) is located above the momentum absorber. In a measurement the beam is allowed to strike the test surface and the balance deflection is recorded. The beam chamber is then moved downward mechanically so that the beam enters the momentum absorber, and the corresponding balance deflection is recorded. The ratio of these two deflections then gives

$$R = \frac{p_i + p_n}{p_i + p_a} \quad ,$$

where p_a is the momentum due to the molecules leaving the momentum absorber and has a maximum value for these experiments of around $0.055\ p_i$. If one assumes that the molecules collide with the walls of the momentum absorber a sufficiently large number of times that they are in thermal equilibrium with the walls and leave with a corresponding velocity and angular distribution, then by knowing the temperature of the walls p_a can be calculated, and $\frac{p_n}{p_i}$ can be easily computed from

$$\frac{p_n}{p_i} = R\left(1 + \frac{p_a}{p_i}\right) - 1 \quad .$$

Since p_a is a small fraction of p_i the precise validity of the above assumption does not strongly affect the calculated values of $\frac{p_n}{p_i}$. The assumption concerning the effectiveness of the momentum absorber will be discussed further in Section IV.

In the measurements to be discussed in the next section the neutralization cell is located about 18 cm from the test surface on the torsion balance. This allows a considerable distance within which the neutral beam can diverge appreciably, especially at the low energies where the ion beam before neutralization is expected to be rather divergent. The diameter of the beam at the test surface was found to be around 1 - 1.5 cm. Since it is difficult to construct a satisfactory balance with the test surface and the entrance aperture of the momentum absorber as large as this, some means was necessary to collimate the neutral beam before it reached the balance. This was accomplished by placing two collimating 7 mm dia. holes, one above the other, just before the

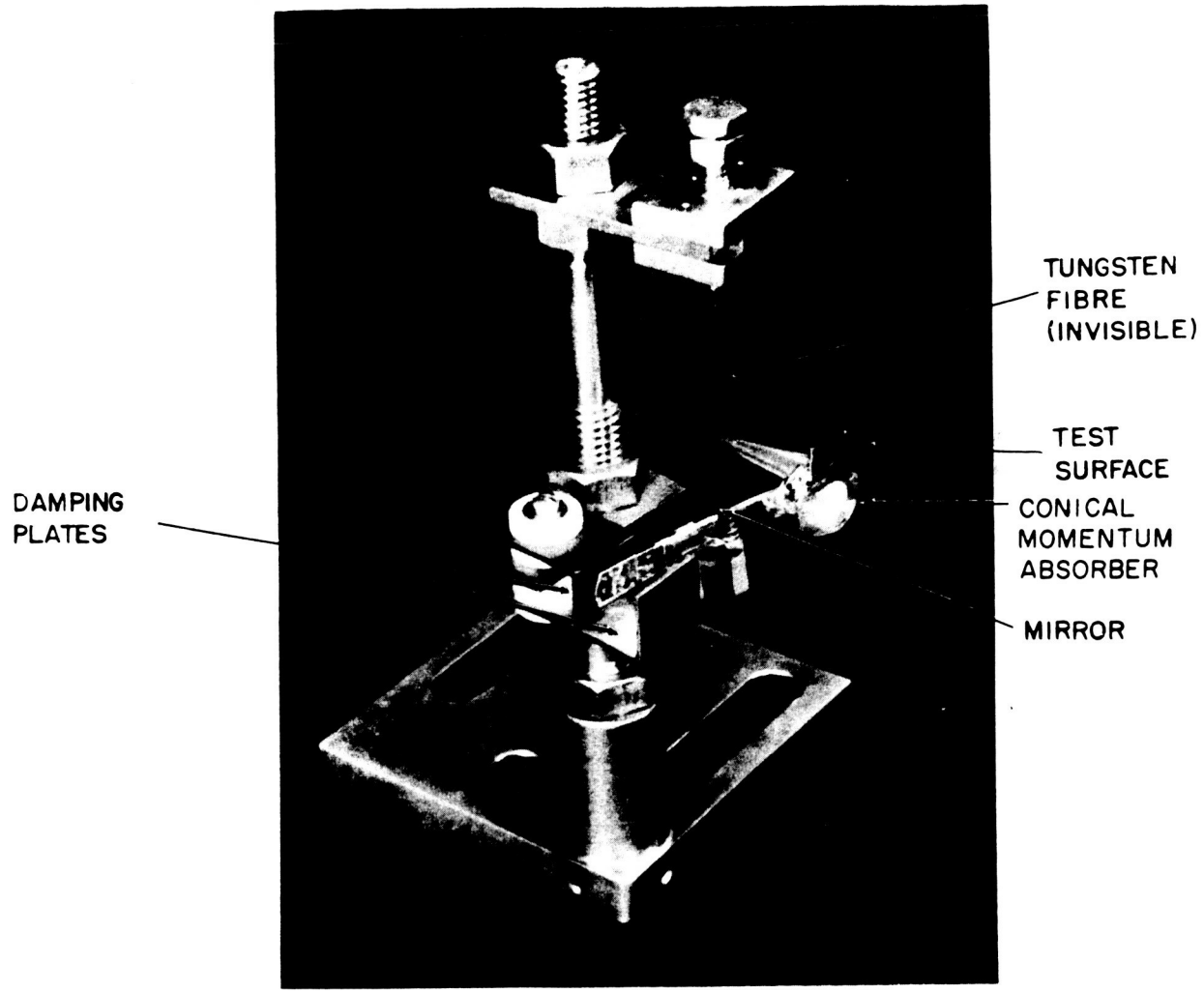

FIGURE 2

TORSION BALANCE

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balance. The diameter of the holes is such that all of the beam passing through the top hole will strike the test surface and all of the beam passing through the bottom hole will enter the momentum absorber. The measurement is then performed by closing the bottom hole with a shutter, allowing a portion of the beam to pass through the upper hole and strike the test surface, and recording the corresponding balance deflection. The beam chamber is then moved downward a distance equal to the separation between the two holes, the top hole is closed and the bottom one opened, the same portion of the beam is allowed to pass through the bottom hole and enter the momentum absorber, and the balance deflection is recorded. The ratio of these two deflections, then, gives the value of R.

Because of the nature of the method used to produce the beam there are forces on the balance in addition to the desired force. This requires that the method used to obtain the balance deflection should eliminate any effects due to these extraneous forces. First, there is a force on the balance produced by N_2 gas effusing from the neutralizing cell. Some of the measurements reported here were made when cryogenic pumping of the neutralizing gas was not used, which means that the force due to this gas may be considerably larger than that caused by the molecules of interest. Second, there can be a force produced by high energy neutral molecules that were produced by charge transfer of beam ions in the residual gas of the beam chamber at points within the electrostatic focusing system where the ion energy is higher than the desired energy. One must then have a method of obtaining balance deflections which are due only to the desired neutral beam molecules and are not affected by the magnitude of these extraneous forces. This is accomplished by allowing all of these molecules to strike the balance and then measuring the balance deflection that results when the molecules of interest are prevented from reaching the balance. This in effect allows one to ignore the effect of the unwanted molecules. The molecules of interest (which in previous discussion we have called the beam) are prevented from reaching the balance by changing the potential on an electrode just before the neutralization cell so that the ions cannot enter the cell. This eliminates the force on the balance

caused by the neutral molecules formed by neutralization of these ions, but does not affect the forces due to the effusing gas molecules and the high energy neutrals. The corresponding balance deflections caused by turning the ion beam on and off in this manner is then the desired deflection. This procedure is, of course, repeated for both the test surface and the momentum absorber.

Generally four or five measurements are taken with the beam striking the test surface, then a similar number with the beam entering the momentum absorber, and then another set with the test surface. The average for the test surface is then compared to the average for the momentum absorber. The fact that a complete measurement includes two sets for the test surface tends to minimize the effect of slowly changing beam conditions.

The measurements were performed for several different test surfaces. The entire question of surface condition in experiments such as these involves a number of uncertainties. In considering the application of the measurements to satellite studies of the density of the earth's upper atmosphere, one would like to make the measurements using samples of actual satellite surfaces which have the same surface condition as that of the satellite in orbit (especially regarding adsorbed gases on the surface). There are two reasons why this desirability cannot be achieved at present. First, the condition of the satellite's surface is to a large extent unknown. It depends on the preparation of the satellite, its environment in orbit, and possible continual emission of gases from portions of the satellite. Second, even the most advanced laboratory techniques are not presently capable of specifying precisely the condition of a surface under study. It is possible, however, that some aspects of the molecule-surface interaction are not especially sensitive to the exact nature of the surface, particularly aspects that involve averages over a number of parameters. Since the momentum transfer measurements described here provide a rather coarse study of the interaction, the following philosophy has been adopted with regard to surface condition. The measurements are performed for several test surfaces, but the exact condition of the surface is not rigidly controlled. The surfaces are handled carefully before placing them in the vacuum system so as to prevent their being contaminated by oils, fingerprints,

etc., but no attempt is made to remove adsorbed gases from the surfaces after they are in the vacuum system and the measurements are performed at pressures ($\sim 10^{-6}$ Torr) such that a clean surface (no adsorbed gases) cannot be maintained. If the results of the measurements indicate that only the gross character of the surface (such as surface roughness) affects the momentum transfer, then one might conclude that the surfaces can be adequately characterized for this particular type of measurement. Measurements that investigate finer details of the interaction, such as the angular and velocity distribution of the reflected particles, may require considerably more accurate surface characterization.

SECTION III
RESULTS

The objective in these measurements is to investigate $\frac{p_n}{p_i}$ as a function of molecule energy and angle of incidence for several test surfaces, including samples of surfaces used on actual satellites. The results of these measurements are presented in Tables I-VII and Figures 3-7. A plot of $\frac{p_n}{p_i}$ against molecule energy in the range 10-200eV is shown in Figures 3 and 4 for several surfaces and normal incidence ($\theta=0°$). It is seen that the results are essentially the same for all of the surfaces studied. One of the principal factors in determining the nature of the particle-surface interaction is the ratio of the masses of the incident molecule and the surface atoms that it strikes. For this reason a measurement has been included for a gold surface (mass number 197) to see if the results are affected by a large change in the mass number of the base material. The fact that the results for gold are essentially the same as for the other surfaces indicates that under the conditions of these measurements the interaction with adsorbed gases predominates.

A straight-forward investigation of the dependence of the ratio $\frac{p_n}{p_i}$ on the angle of incidence would involve mounting the test surfaces on the balance vane so that the beam molecules strike the surface at the chosen angle, but with the beam direction still perpendicular to balance vane. This means that the balance must be modified or reconstructed for each new angle. At angles of incidence less than 32° this procedure was followed with success. At larger angles, however, it was found that the combination of the mass of the momentum absorber and that of the larger test surface needed to intercept all of the beam passing through the collimating aperture caused the balance to be intolerably noisy. Since all the surfaces studied gave essentially identical results it was decided that the measurements at larger angles would be performed by eliminating the momentum absorber and using one of the surfaces studies earlier (at $\theta=0°$) as a reference surface, thereby reducing the mass mounted on the balance arm. The ratio $\frac{p_n}{p_i}$ for the larger angles can thus be obtained by comparing deflections for the inclined surface and the reference surface, and then

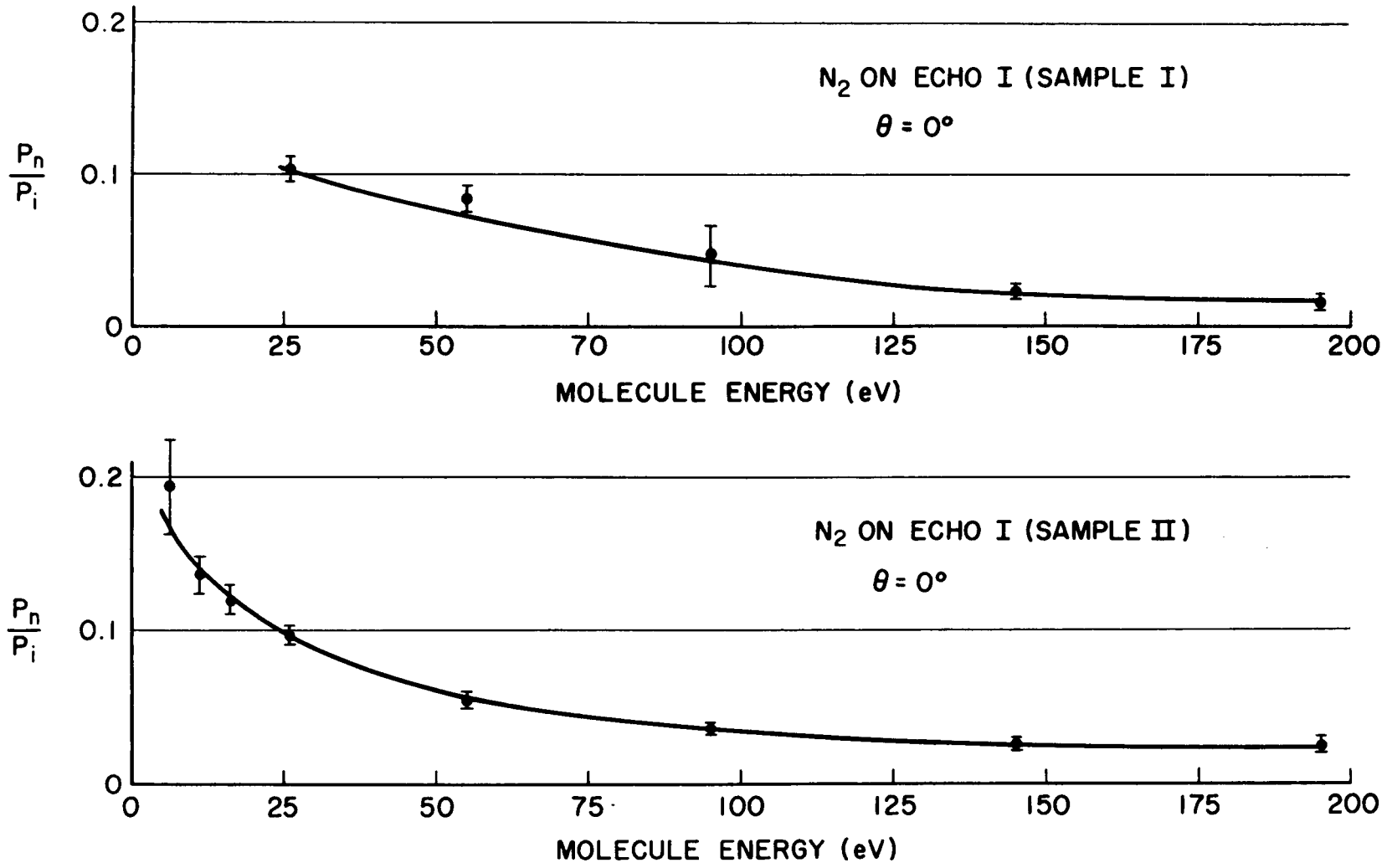

FIGURE 3
MOMENTUM TRANSFER RESULTS AT $\theta = 0°$

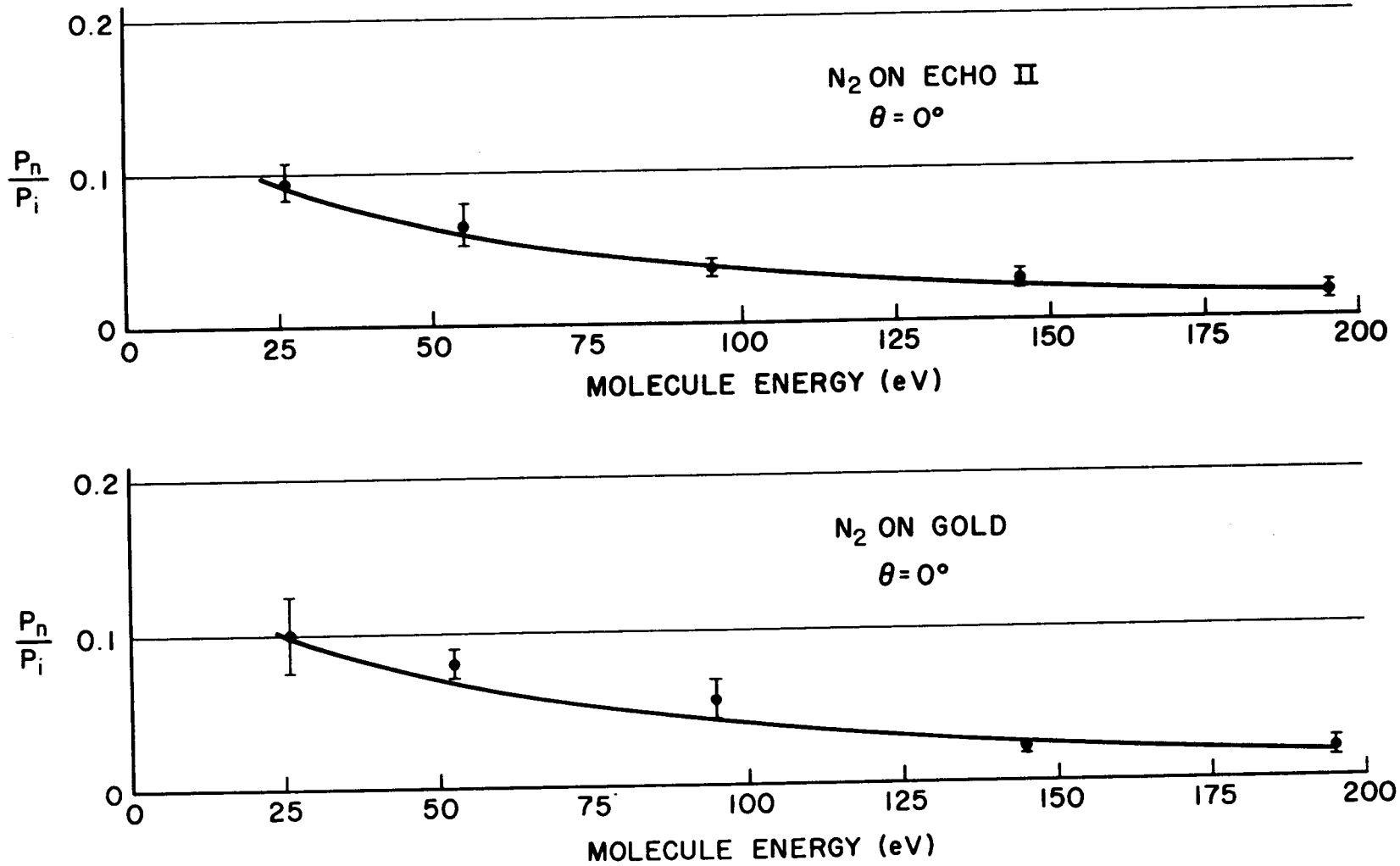

FIGURE 4
MOMENTUM TRANSFER RESULTS AT $\theta = 0°$

using the results obtained previously which provided a comparison of the reference surface with the momentum absorber. If the deflection for the inclined surface divided by the deflection for the reference surface is called S, then

$$S = \frac{p_i + p_n}{p_i + p_{no}} = \frac{1 + \frac{p_n}{p_i}}{1 + \frac{p_{no}}{p_i}} \quad ,$$

where p_{no} is the value of p_n for the reference surface for $\theta = 0$. Also,

$$R_o = \frac{p_i + p_{no}}{p_i + p_a} = \frac{1 + \frac{p_{no}}{p_i}}{1 + \frac{p_a}{p_i}} \quad ,$$

where R_o is the value of R for the reference surface at $\theta = 0$. Eliminating $\frac{p_{no}}{p_i}$ between the expressions for S and R_o and solving for $\frac{p_n}{p_i}$ one gets

$$\frac{p_n}{p_i} = S R_o\left(1 + \frac{p_a}{p_i}\right) - 1 \quad .$$

This is the expression used for obtaining $\frac{p_n}{p_i}$ for the larger angles of incidence where one is comparing the force on an inclined surface to that on a reference surface.

The experimental results for two surfaces at $\theta = 32^o$ are shown in Figure 5. Figure 6 shows a plot of $\frac{p_n}{p_i}$ for N_2 on a rough (abraded) copper surface at $\theta = 60^o$. These measurements were made by comparing deflections for $\theta = 0^o$ for Cu with $\theta = 60^o$ for Cu. In reducing the data for Figure 6 it was assumed that R_o for copper was the same as for the other surfaces studied. Also plotted in Figures 5 and 6 is the behavior one would expect if the reflected momentum vector p_r (assumed to have the same magnitude at different angles) were (a) normal to the surface and (b) at the specular angle. The curve for specular reflection is not plotted in Figure 6 since $\frac{p_n}{p_i}$ is negative for this case.

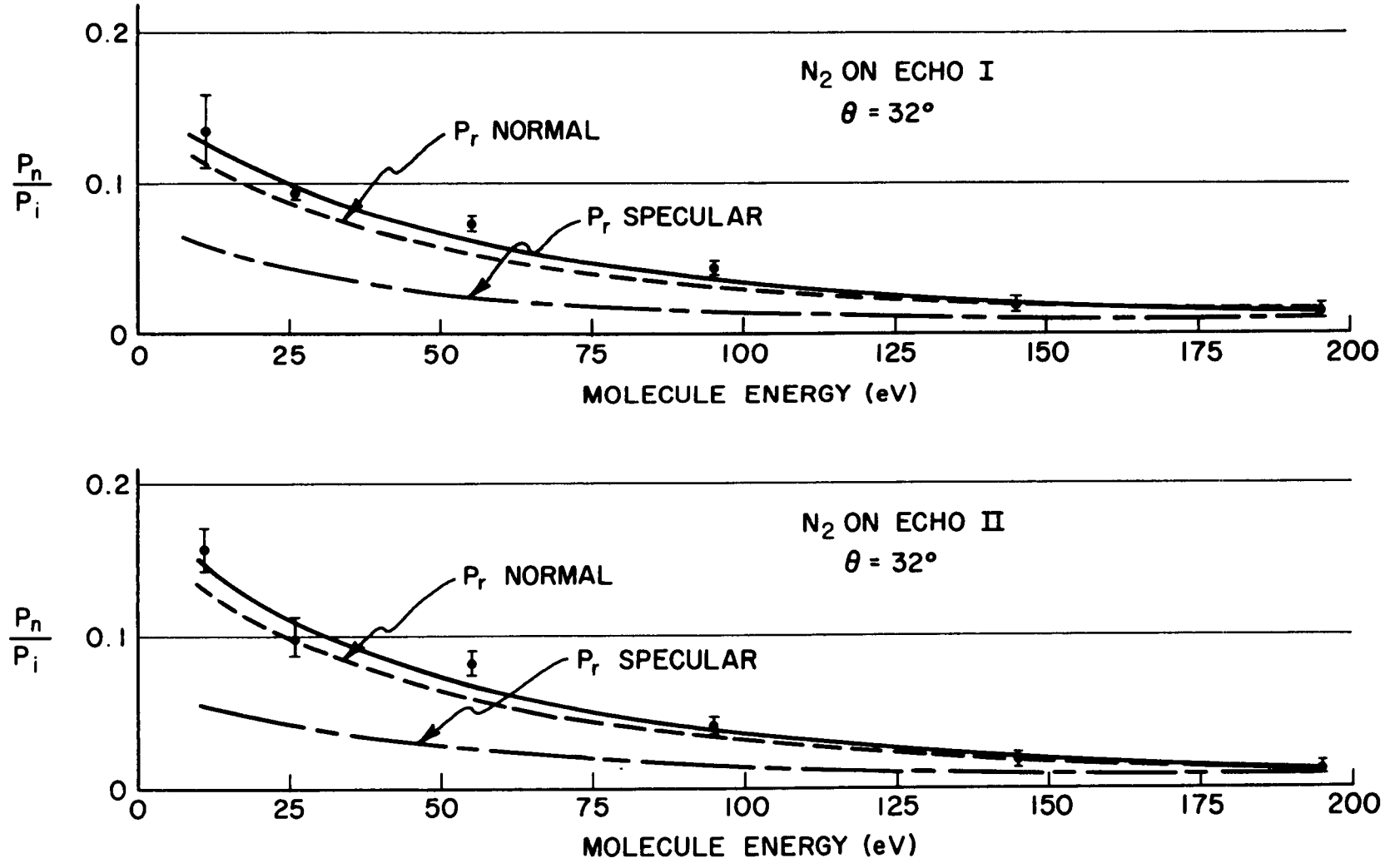

FIGURE 5

MOMENTUM TRANSFER RESULTS AT $\theta = 32°$

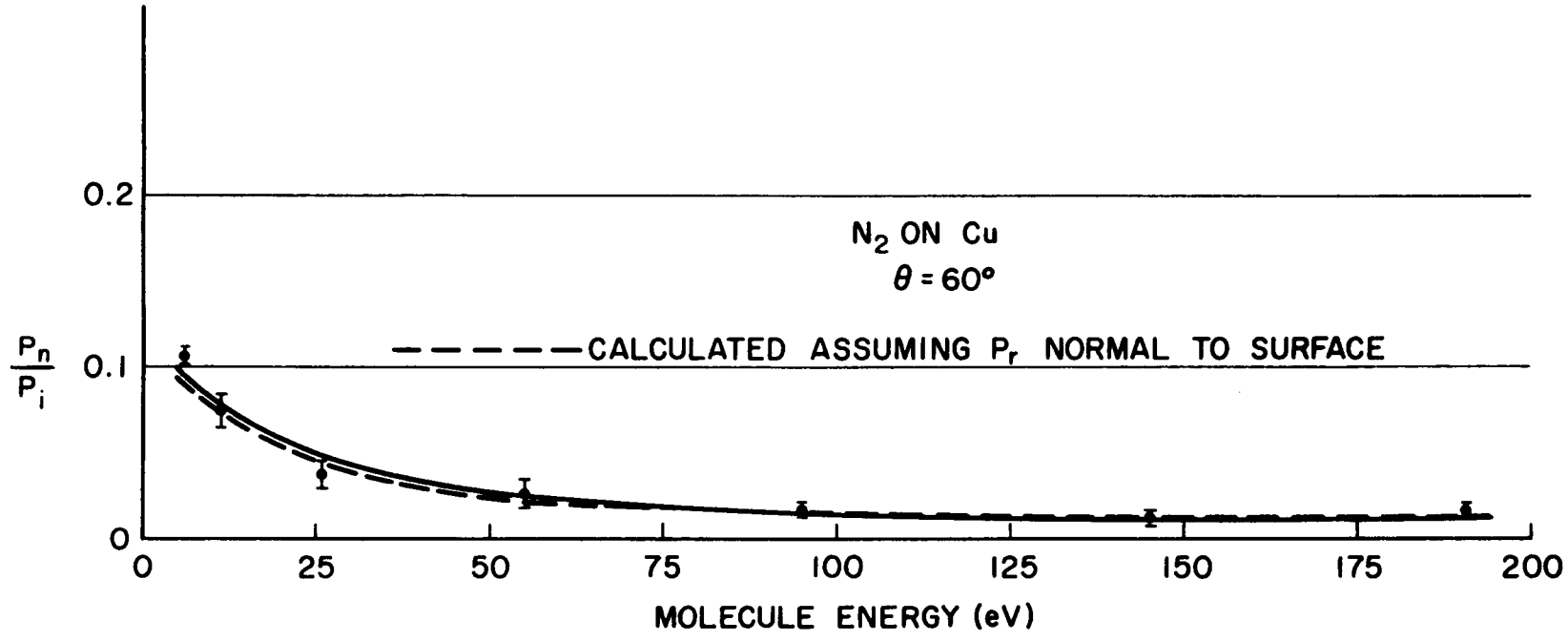

FIGURE 6

MOMENTUM TRANSFER RESULTS AT $\theta = 60°$

Although the number of angles studied is small, it is clearly indicated that at least for relatively rough surfaces within the angular range 0-60° the reflected molecules come off very nearly normal to the surface. It is possible that the magnitude and direction of p_r both depend on angle of incidence in such a way as to give the same component along the beam direction as if p_r were constant in magnitude and normal to the surface. However, it would seem highly coincidental that this is the case for the entire range of energies studied as the results of Figure 4 indicate. Measurements with other surfaces and different angles will be helpful in establishing more precisely the direction of p_r. The conclusion here that at least for rough surfaces the direction of p_r is independent of angle of incidence is supported by the measurements of Marsden, Abauf, and Fenn[4] who studied the momentum transfer to "engineering" surfaces by argon and helium atoms at energies up to 4.1 eV. They measured the momentum transfer normal to the surface for several surfaces and found that in the range of incident angles $0<\theta<81^\circ$ the normal momentum transfer (force normal to the surface) was always proportional to cos θ. This indicates that for these measurements p_r has a magnitude that is independent of θ and a direction that is either normal to the surface or along the specular direction.

The measurements (Figure 6) on a rough copper surface at $\theta = 60^\circ$ indicate that the momentum vector of the reflected molecules is very close to being normal to the surface. In light of the fact that all of the measurements at $\theta = 0^\circ$ have indicated no appreciable differences which may be attributed to the nature of the surface, it was concluded at the time of the copper measurements that it was probable that p_r was normal to the surface for all surfaces of the type studied here. This was the state of affairs at the time of the completion of the period covered by this report (October 1966). Recent measurements, however, have indicated that for a relatively smooth surface (Echo I, aluminum evaporated on Mylar) at $\theta = 60^\circ$ the reflected momentum vector is displaced considerably from the normal. This means that although the conclusions given above concerning the direction of p_r may be valid for surfaces that are rough on a molecular scale, they should not be used for smooth surfaces. Additional measurements will therefore be required to permit one to calculate drag coefficients for satellites with relatively smooth surfaces.

SECTION IV
DISCUSSION

The principal conclusions to be drawn from the results presented in the previous section are: (1) For surfaces covered with adsorbed gases the results appear not to depend on the underlying surface material. (2) The ratio $\frac{p_n}{p_i}$ changes smoothly from about 0.12 at 10 eV to around 0.01 at 200 eV. (3) The average reflected momentum vector, p_r, for a rough surface appears to have a magnitude that does not depend on the angle of incidence and is directed normal to the surface. The information contained in the data and the conclusions drawn from the data are sufficient to allow one to calculate fairly accurately the drag coefficient for a satellite moving through a rarefied atmosphere of N_2 gas (or give the contribution due to the N_2 molecules in a mixed atmosphere) as long as the surface of the satellite is rough on a molecular scale. Additional information is required, however, before one can provide a satisfying and complete relation between satellite drag and the density of the upper atmosphere for all types of surfaces.

It is seen in Figure 3 that the ratio $\frac{p_n}{p_i}$ depends fairly sensitively on energy in the vicinity of 10 eV. It would thus be desirable to extend the measurements down to around 5 eV so as to include the entire velocity range encountered in satellite motion (6-12 km/sec). One should also extend the measurements to include other atmospheric species, especially O and He atoms. Additional measurements with N_2 molecules should be made for smooth surfaces and surfaces made intentionally rough, so that one can more accurately assess the effect of a drastic change in the surface.

In the discussion in Section III it was assumed that the molecules leaving the momentum absorber had a cosine angular distribution and a Maxwellian distribution of velocities which was characteristic of the temperature of the walls of the absorber. Since the absorber is constructed so that the molecules must on the average collide around 20 times with the walls before leaving, the real question concerning its effectiveness is how much is the energy of the molecules

reduced in each collision with the wall. Or, in other words, what is the thermal accomodation coefficient for the N_2 molecules colliding with the walls of the absorber. The thermal accomodation coefficient is defined as

$$\alpha = \frac{E_i - E_r}{E_i - E_w} \quad ,$$

where E_i is the energy of the incident particles, and E_r is the energy of the reflected particles, and E_w is the energy the reflected particles would have if they left with an energy characteristic of the temperature of the surface (all energies are average values). If (as in the present experiment) $E_w << E_i$, then

$$\frac{E_r}{E_i} = 1 - \alpha ,$$

or if one calls E_f the final energy after x collisions with the absorber walls we get approximately

$$\frac{E_f}{E_i} = (1 - \alpha)^x$$

For $E_f \sim \frac{1}{40}$ eV (thermal), E_i = 10 eV, and X = 20 collisions then we find that one must have α greater than around 0.25 for 10 eV molecules to become thermalized within the momentum absorber. Although the available measurements[5] of accomodation coefficients for N_2 molecules on gas covered room temperature surfaces give values in the range $0.7 < \alpha < 0.9$, these measurements have all been for incident energies in the thermal range. One really needs information on accomodation coefficients for energies in the range studied in the present experiment (at least for the first collision with the walls of the absorber), and no such values are currently available. However, since one only needs to know whether or not $\alpha > 0.25$, it is reasonable to use the high energy limit of theoretical calculations of the accomodation coefficient. One of the best known of such limits is that obtained by Baule[6] which gives

$$\alpha = \frac{2\mu}{(1 + \mu)^2} \quad ,$$

when averaged over incident angles. If for gas covered surfaces one chooses $\mu = 1$ (ratio of mass of incident particle to that of surface particle) we get $\alpha = 0.5$. We can also note that accomodation coefficients derived from momentum transfer measurements[4] for 4 eV argon atoms on gas covered surfaces give $0.5 < \alpha < 0.7$, indicating that the available theoretical and experimental information on energy accomodation at eV energies gives values of α that easily satisfy the above condition for the effectiveness of the momentum absorber.

Since there have been very few experimental studies of the interaction between neutral molecules and solid surfaces for particle energies in the eV range, it is of interest to compare the present results to current theories of the particle-surface interaction. A comparison has therefore been made with the formulas of Goodman and Wachman[7] who have used the development obtained by Goodman[8] using a classical model of the particle-surface interaction.

One is primarily interested in comparing the energy dependence of the experimental results with the theoretical prediction. Figure 7 shows a plot of the averages of $\frac{p_n}{p_i}$ for several surfaces against energy along with calculated values for $\frac{p_n}{p_i}$. The calculated values are obtained from[7]

$$\frac{p_n}{p_i} = \frac{2}{3} (1 - \Gamma_2)^{1/2} ,$$

where $\Gamma_2 = 1 - \frac{U_n^2}{U_i^2} = A(\mu) \tanh (B U_i)$,

U_n and U_i are the reflected and incident molecule velocities, μ is the ratio of masses of the incident and surface molecules, B is a constant which is characteristic of the surface, and $A(\mu)$ is the high energy limit of Γ_2. In the above the diffuse distribution is assumed for the reflected molecules, and the analytic form of Γ_2 is determined largely by its ability to describe the high energy portion of thermal accomodation coefficient data[7]. The experimental data in Figure 7 indicate that one should take $A(\mu) = 1$. Since for the conditions of this experiment

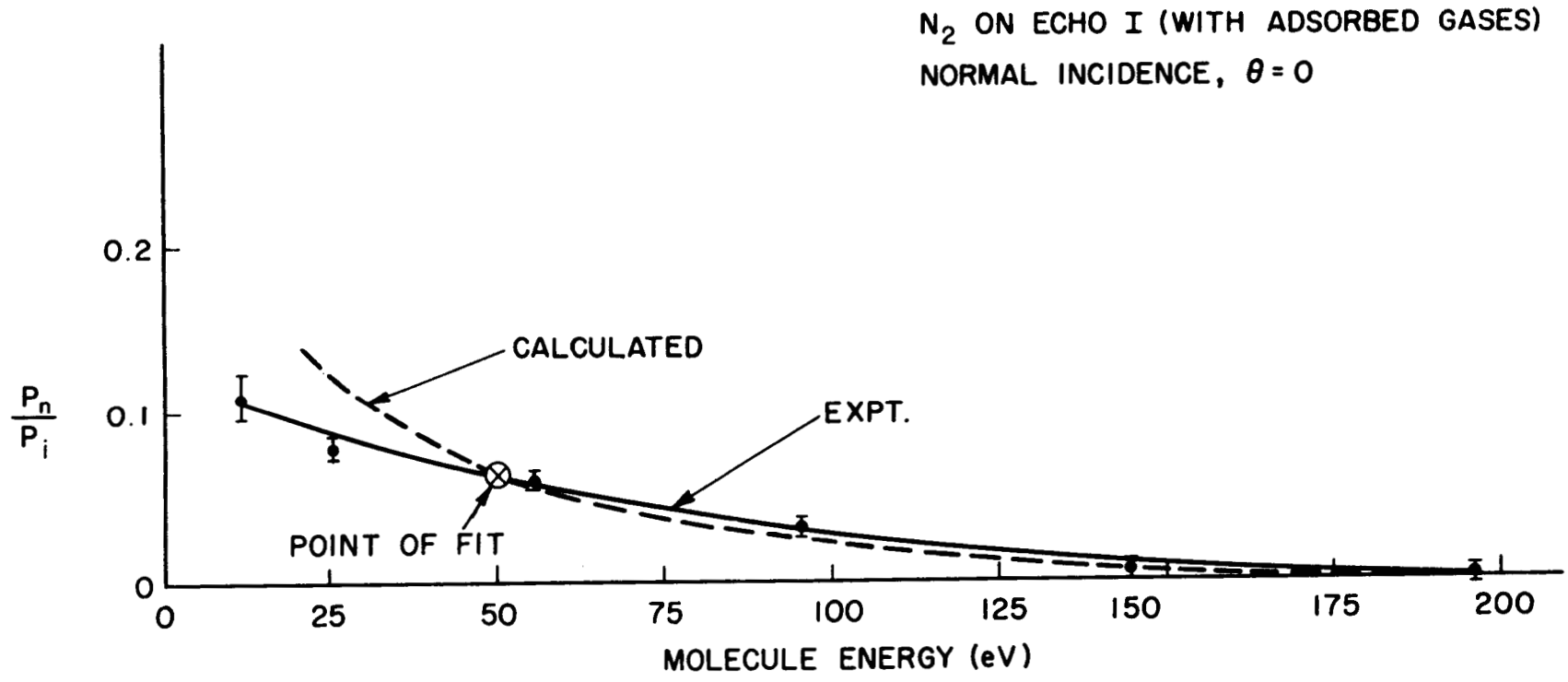

FIGURE 7
COMPARISON OF EXPERIMENT WITH HIGH-ENERGY THEORY

the interaction appears to be primarily with adsorbed gases on the surfaces, there is no basis for choosing a value of B which is characteristic of the underlying target material, so a value of $B = 1.5 \times 10^{-4} \left(\frac{m}{sec}\right)^{-1}$ has been chosen to provide a fit to the experimental data at the arbitrarily chosen energy of 50 eV. This value of B is in the neighborhood of those used to obtain agreement with measurements of thermal accomodation coefficients[5], but the value of $A(\mu) = 1$ is larger than one would get by using the maximum of the Goodman and Wachman expression

$$A(\mu) = \frac{3.6\mu}{(1+\mu)^2}$$

for molecules of equal mass.

It is seen in Figure 7 that the calculated curve and the experimental data agree rather well at energies above the point of fit (50 eV). This is not too surprising in view of the fact that the experimental curve is rather smooth and two adjustable parameters, $A(\mu)$ and B, have been used to fit to the data, but the values chosen for these parameters appear reasonable.

It is anticipated that in the next year's work the measurements for momentum transfer by N_2 molecules will be extended to cover a greater number of surfaces and angles and down to energies around 5 eV (v=5.9 km/sec). In addition, a system for producing a suitable beam of oxygen atoms will be developed and the momentum transfer measurements will be extended to include this species. The feasibility of producing a suitable beam of He atoms will also be studied.

TABLE I

N_2 on Echo I, $\theta = 0°$ (Sample I)

E_i (eV)	V_i (km/sec)	$R = \frac{p_i + p_n}{p_i + p_a}$	$\frac{p_a}{p_i}$	$\frac{p_n}{p_i}$
26	13.3	1.070	.029	.101±.006
55	19.4	1.062	.020	.083±.009
95	25.6	1.033	.015	.048±.018
145	31.6	1.011	.012	.023±.001
195	36.6	1.007	.010	.017±.006

TABLE II

N_2 on Echo I, $\theta = 0°$ (Sample II)

E_i (eV)	V_i (km/sec)	$R = \frac{p_i + p_n}{p_i + p_a}$	$\frac{p_a}{p_i}$	$\frac{p_n}{p_i}$
7	6.9	1.133	.055	.195±.038
12	9.1	1.092	.042	.137±.015
16.5	10.7	1.082	.036	.120±.010
26	13.3	1.065	.029	.096±.005
55	19.4	1.033	.020	.054±.005
95	25.6	1.022	.015	.037±.001
145	31.6	1.015	.012	.027±.003
195	36.6	1.017	.010	.027±.005

TABLE III

N_2 on Echo II, $\theta = 0°$

E_i (eV)	V_i (km/sec)	$R = \frac{p_i + p_n}{p_i + p_a}$	$\frac{p_a}{p_i}$	$\frac{p_n}{p_i}$
26	13.3	1.063	.029	.094±.015
55	19.4	1.045	.020	.066±.015
95	25.6	1.022	.015	.037±.004
145	31.6	1.017	.012	.029±.005
195	36.6	1.007	.010	.017±.004

TABLE IV

N_2 on Gold, $\theta = 0°$

E_i (eV)	V_i (km/sec)	$R = \frac{p_i + p_n}{p_i + p_a}$	$\frac{p_a}{p_i}$	$\frac{p_n}{p_i}$
26	13.3	1.070	.029	.100±.026
55	19.4	1.060	.020	.081±.010
95	25.6	1.040	.015	.057±.016
145	31.6	1.010	.012	.022±.005
195	36.6	1.010	.010	.020±.010

TABLE V

N_2 on Echo I, $\theta = 32°$

E_i (eV)	V_i (km/sec)	$R = \frac{P_i + P_n}{P_i + P_a}$	$\frac{P_a}{P_i}$	$\frac{P_n}{P_i}$
12	9.1	1.088	.042	.135±.020
26	13.3	1.063	.029	.094±.003
55	19.4	1.052	.020	.073±.003
95	25.6	1.027	.015	.042±.004
145	31.6	1.006	.012	.018±.005
195	36.6	1.004	.010	.014±.004

TABLE VI

N_2 on Echo II, $\theta = 32°$

E_i (eV)	V_i (km/sec)	$R = \frac{P_i + P_n}{P_i + P_a}$	$\frac{P_a}{P_i}$	$\frac{P_n}{P_i}$
12	9.1	1.110	.042	.157±.012
26	13.3	1.068	.029	.099±.012
55	19.4	1.061	.020	.082±.008
95	25.6	1.025	.015	.040±.005
145	31.6	1.005	.012	.017±.003
195	36.6	1.002	.010	.012±.002

TABLE VII

N_2 on Cu, $\theta = 60°$

E_i (eV)	V_i (km/sec)	$S = \frac{p_i + p_n}{p_i + p_{no}}$	$R_o = \frac{p_i + p_{no}}{p_i + p_a}$	$\frac{p_a}{p_i}$	$\frac{p_n}{p_i}$
7	6.9	.924	1.133	.055	.105±.007
12	9.1	.944	1.092	.042	.074±.014
26	13.3	.948	1.065	.029	.039±.007
55	19.4	.976	1.033	.020	.028±.009
95	25.6	.982	1.022	.015	.018±.002
145	31.6	.984	1.015	.012	.011±.002
191	36.6	.991	1.017	.010	.018±.001

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